Curved Displays Challenge Display Metrology

Non-planar displays require a close look at the components involved in taking their measurements.

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DISPLAY metrology — measurement and evaluation of the electro-optical properties of display devices — is crucial in order to obtain objective characteristics that specify the performance of such displays as a basis for purchasing decisions. The usability of displays for a certain application can be estimated on the basis of performance features obtained from standardized display measurements (see, for example, ISO-9241-3xx). In the R&D activities of companies that are manufacturing displays and products with displays, display metrology is necessary to obtain performance specifications for systematic product optimization.[1]

Measurement and evaluation of the electro-optical performance of display devices are based on the target quantities ***luminance*** (corresponding to the visual perception of brightness) and ***chromaticity*** (corresponding to the visual perception of color). They comprise four main components:

- lateral variations,
- directional variations,
- variations vs. electrical input,
- temporal variations (long and short term).

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Evaluation of the recorded target quantities generally yields uniformities (or inversely, non-uniformities) and characteristic functions; that is, variations of the target quantity (electro-optical transfer function, or EOTF) from which characteristic values can be obtained (*e.g.*, the exponent gamma from the EOTF).

Emissive displays — a fixed combination of transmissive LCD and backlight unit (BLU) can be considered as an emissive display — can be measured under darkroom conditions, but more realistic results are obtained when controlled ambient illumination is provided during the measurements. Reflective displays require external illumination sources to function. Realization of controlled illumination is quite demanding and usually makes display metrology even more complex and delicate to handle.

A basic difficulty of electro-optical display metrology, not unlike metrology in other technical fields, is the reproducibility of the results — that is, the ability to obtain the same results across a range of laboratories, measurement setups, and operators. A necessary condition for reproducibility is the exact knowledge and specification of all measurement conditions, comprising the display under test (DUT), the light measurement devices (LMDs), their condition of application (*i.e.*, the measurement setup, including illumination devices), and the procedure.

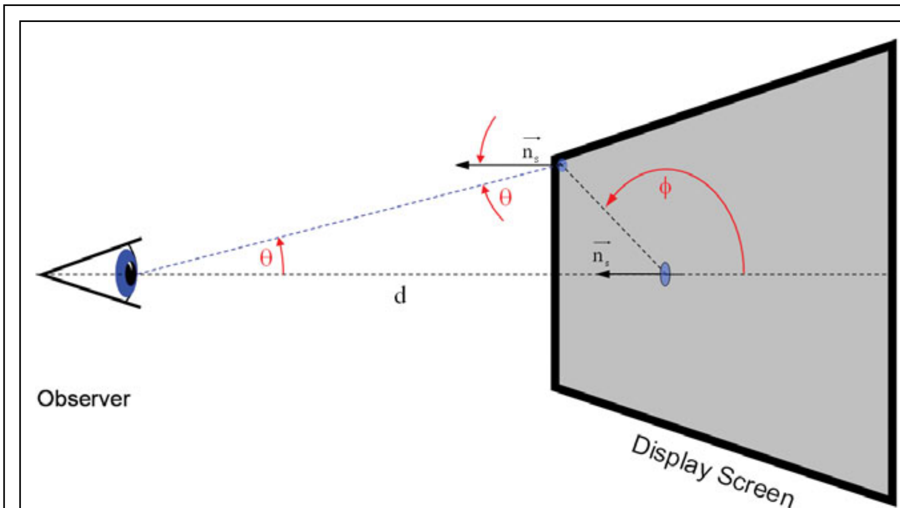

Fig. 1: The observer looks at every location on the display screen from a specific direction (viewing direction) specified by the spherical angles, θ (angle of inclination) and ϕ (azimuth).

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This article describes the effect of the measurement field diameter and the LMD aperture on the directions included in one measurement for both spot LMDs and imaging LMDs for displays in general, and it points out the effect of the local display curvature. It identifies the critical aspects, evaluates the maximum angle of inclination quantitatively, and proposes precautions for routine measurements in the optical laboratory to yield reproducible and significant results.

Curved Displays

Curved displays were introduced to the TV segment of the display market some years ago with the objective of providing the user (observer) with a more "immersive viewing experience." For TV and computer-monitor applications, the curvature is typically concave.

In the automotive-instrumentation sector, curved-form factors have been introduced to obtain a more seamless fitting of displays into the dashboard assembly — that is, the curvature is a design feature rather than an improvement on customer experience. In the automotive world, quality control is highly important in order to assure compatibility throughout the complete supply chain. This also requires unambiguous, well-specified, and standardized test and measurement procedures as a basis for reproducibility.

Convex-shaped displays are also encountered as wearable displays, especially when designed and worn as wristbands.

Variation of Perspective

When we observe a display screen, as sketched in Fig. 1, we look at each location on the screen from a specific direction (*i.e.*, viewing direction). This direction is specified by two spherical angles, the angle of inclination, θ (with respect to the display surface normal, n_s), and the azimuth, ϕ, with respect to a reference direction within the screen surface area (here: 3 o'clock direction) as indicated in Fig. 1. The viewing direction can be calculated from the viewing distance, d, and the coordinates of the location the observer is looking at. The corners of an office desktop monitor with 23-in. screen diagonal and a 16:9 aspect ratio are seen at an angle of inclination of 20° when the observer is 800 mm away from the screen center. Since the variation of luminance is usually continuous and gradual from the center to the corners, this variation is not readily visible to the human observer; however, it may have a pronounced effect on optical measurements.

Typical Objects of Measurement

The optical properties of display devices (luminance and chromaticity) generally are a function of the direction of observation (viewing direction), not only in the case of LCDs but — in contrast to conventional wisdom and rather unexpected also for experts — also in the case of OLED displays.

Figures 2 and 3 illustrate the variation of luminance and chromaticity (Δ*u'v'*) of a typical active-matrix-addressed OLED display (Fig. 2) and of a typical high-quality LCD screen (Fig. 3) with viewing direction in polar coordinate systems where every point corresponds to one viewing direction specified by angle of inclination, θ, and azimuth, ϕ, in the upper row. The variation with angle of inclination, θ, with the azimuth as parameter is shown in the lower rows. These results are typical for current state-of-the-art display screens used in high-quality portable devices like smartphones.

The luminance decreases with angle of inclination; in the case of the OLED display, it decreases in a rotationally symmetric way. While the variation of chromaticity difference Δ*u'v'* (related to the normal direction) is larger for the OLED display, the luminance drop with angle of inclination is more pronounced for the liquid-crystal (LC)-display. Both variations are more rotationally symmetric in the case of the OLED display.

The corner locations of a computer monitor (23-in. screen diagonal and viewing conditions as introduced above) with a perfect lateral uniformity of luminance, would be

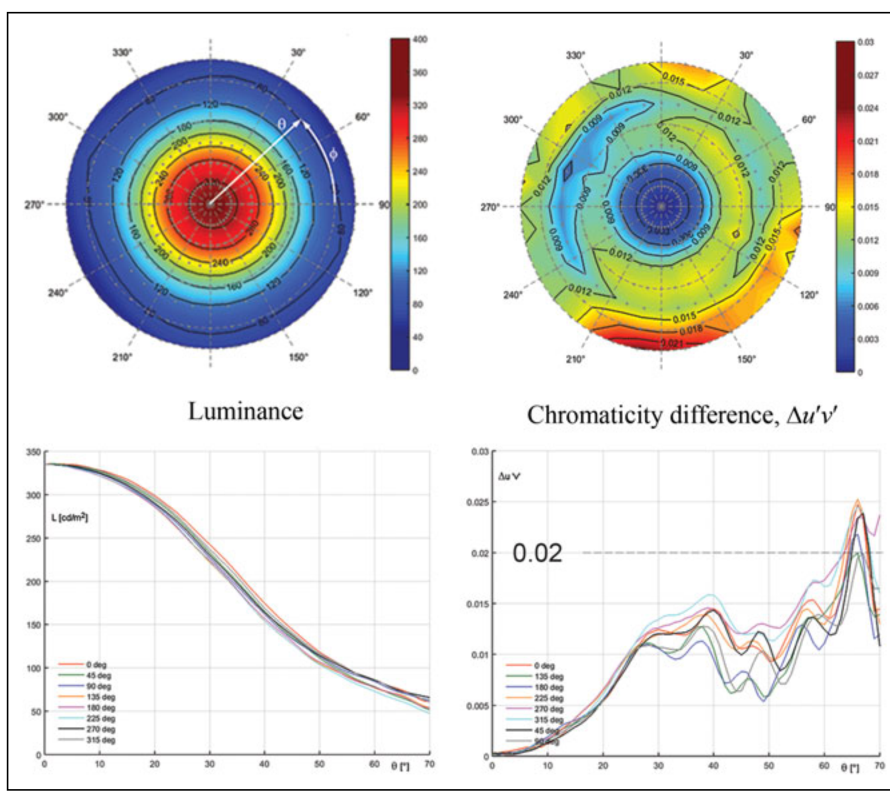

Fig. 2: Above is shown the variation of luminance (L) and chromaticity (Δu'v') with viewing direction (θ, ϕ) for the white state of an active-matrix-addressed OLED display. Variations are shown by pseudo-color representations in polar coordinate systems (top row) and variation with angle of inclination, θ, with the azimuth as parameter (bottom row). The luminance decreases about 4 percent (13 percent) at an angle of inclination of 10° (20°). Measurements were performed with the DMS-803.[2]

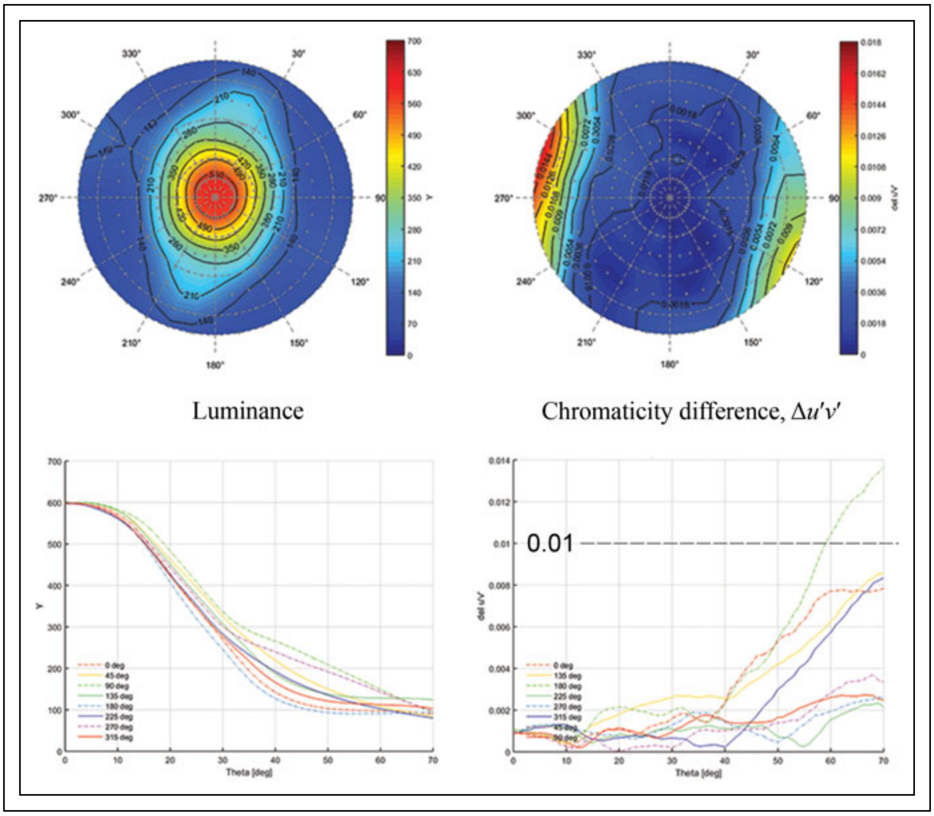

Fig. 3: Above is shown the variation of luminance (L) and chromaticity (Δu'v'), with viewing direction (θ, ϕ) for the white state of an active-matrix addressed LC-display screen. Variations are shown by pseudo-color representations in polar coordinate systems (top row) and variation with angle of inclination, θ, with the azimuth as parameter (bottom row). The luminance decreases about 4 percent (20 to 30 percent) at an inclination of 10° (20°). Measurements were performed with the DMS-803.[2]

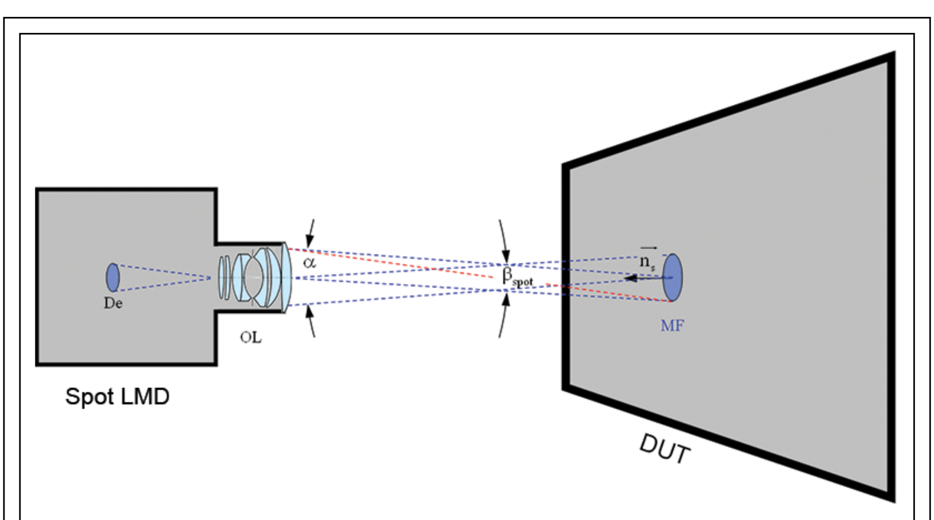

Fig. 4: This schematic shows a spot LMD with opto-electronic detector element (De), objective lens (OL), and a display under test (DUT). The measurement field angle, β_{spot}, usually is 1° or smaller; the aperture angle, α, is given by the clear aperture of the objective lens and the distance to the circular measurement field, MF, on the DUT.

seen as 13 percent (OLED display) or 19 to 32 percent (LC display) darker than the center location due to the decrease of luminance with angle of inclination as illustrated in Figs. 2 and 3, and summarized in Table 2.

Since no displays are currently available with perfectly uniform directional emission characteristics *(Lambertian)*, care has to be taken during measurement to assure that lateral and directional variations are not mixed up, thus affecting the results in a nontrivial, unintended, and nonreproducible way. While this is also true for the measurement of planar displays, it becomes more critical in the case of convex curved displays. It is most important when imaging light measurement devices (iLMDs) are used for "convenient" evaluation of lateral variations of luminance and chromaticity, because the large-measurement-field angles cause a mixing of lateral and directional properties of the display that cannot be separated later on.

Light-Measurement Devices

Depending on the kind of opto-electronic detector used, we can distinguish two classes of light-measurement devices: spot LMDs (LMDs), performing an integration over the measurement field (*i.e.*, measurement spot) and thus delivering one measurement value (for example, luminance), as shown in Fig. 4, and imaging LMDs (iLMDs) with an array of detector elements providing an array of measurement values (see Fig. 6).

As illustrated in Fig. 4, the aperture of the LMD objective lens performs a directional integration over the solid angle α while the detector element performs a lateral integration over the field of measurement. The red ray in Fig. 4 extending from the periphery of the measurement field to the opposite periphery of the lens aperture is the ray with the maximum inclination with respect to the optical axis of the LMD, which is parallel to the surface normal of the DUT, $\vec{n}$.

For evaluation of directional variations, the aperture angle should not exceed 5°, according to IEC 61747-6-2. In typical LMD realizations, the measurement field angle is 1° or smaller (often selectable), and the aperture area of the objective lens is fixed. The distance between the LMD and the DUT determines the actual size of the measurement field on the DUT as well as the aperture angle.

With the quantities illustrated in Fig. 5, the angle of inclination (θ_i) at the periphery of the measurement field (MF) with respect to the local surface normal ($\vec{n}$) is obtained as:[3]

$$\theta_i = \arcsin\left(\sin\left(\arctan\left[\frac{d_A + d_{MF}}{2d_W}\right]\right)\right) \cdot \left[1 + \frac{d_W}{r} - \frac{d_A \cdot d_W}{(d_A \cdot d_{MF}) \cdot r}\right]\quad (1)$$

with

- d_A diameter of the objective lens aperture
- d_W distance between the lens and the measurement field
- d_{MF} diameter of the measurement field
- r radius of the cylindrical DUT

Equation (1) can be used to evaluate the effect of the involved parameters on the range of inclinations over which the LMD integrates ($-\theta_i - +\theta_i$). For planar samples, $r \to \infty$ and thus

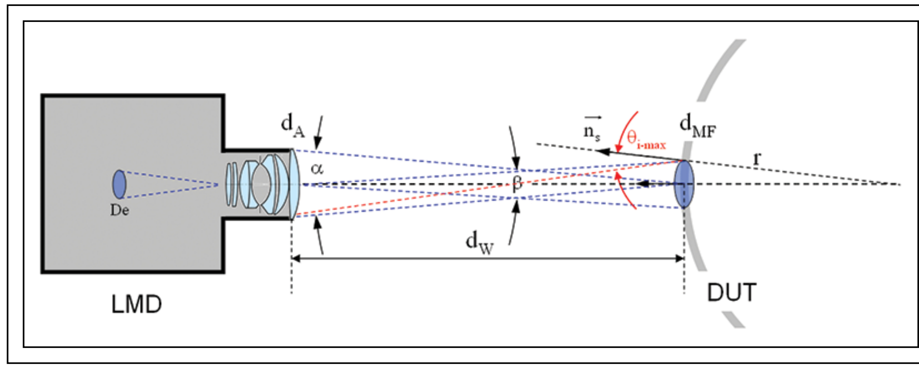

Fig. 5: The angle of inclination (θ_i) at the periphery of the measurement field (MF) with respect to the local surface normal ($\vec{n}$) is given by the diameter of the objective lens aperture (d_A), the distance between the lens and the measurement field (d_W), the diameter of the measurement field (d_{MF}), and the radius of the cylindrical DUT, r.

$$\theta_i = \arcsin\left(\sin\left(\arctan\left[\frac{d_A + d_{MF}}{2d_W}\right]\right)\right)\quad (2)$$

During measurements of cylindrical DUTs with spot LMDs, the diameter of the measurement field should generally be kept as small as possible under consideration of the signal-to-noise ratio of the measurement.

Since the measurement field angle of the LMD is constant by principle (see Fig. 4), the measurement field diameter increases with working distance while the aperture angle, α, continuously decreases. As a result, the angle of inclination at the periphery of the measurement field, $\theta_{i\text{-max}}$, exhibits a minimum when the aperture diameter is not zero. This is the preferred working distance, d_{Wp}, indicated by the yellow cell background in Table 1.

Measurement of Lateral Variations

Lateral variations of luminance and chromaticity are often measured with imaging LMDs because the complete DUT can be captured in "one shot" and no time-expensive

Table 1: Below is shown the angle of inclination at the periphery of the measurement field, $\theta_{i\text{-max}}$, as a function of the measurement field angle, β, the aperture diameter, d_a, the cylinder radius, R_{cyl}, and the working distance, d_w according to Eq. (1). At the preferred working distance, d_{Wp} (yellow cells), $\theta_{i\text{-max}}$ has a minimum. The preferred working distance is indicated by the yellow cell background.

Beta [°]	1															$\theta_{i\text{-max}}$ [°]
da [mm]	10															
	R_{cyl} [mm]	10	20	30	40	50	60	70	80	90	100	200	300	400	500	1000	planar
dw [mm]	d_{MF} [mm]																
50	0.87	8.71	7.46	7.04	6.83	6.71	6.62	6.56	6.52	6.48	6.46	6.33	6.29	6.27	6.26	6.23	6.21
60	1.05	8.27	6.76	6.26	6.01	5.86	5.76	5.69	5.63	5.59	5.56	5.41	5.36	5.33	5.32	5.29	5.26
70	1.22	8.09	6.34	5.75	5.46	5.28	5.17	5.08	5.02	4.97	4.93	4.76	4.70	4.67	4.65	4.62	4.58
80	1.40	8.09	6.08	5.41	5.07	4.87	4.74	4.65	4.57	4.52	4.47	4.27	4.21	4.17	4.15	4.11	4.07
90	1.57	8.19	5.93	5.18	4.80	4.58	4.43	4.32	4.24	4.18	4.13	3.90	3.83	3.79	3.77	3.72	3.68
100	1.75	8.38	5.87	5.03	4.61	4.36	4.19	4.08	3.99	3.92	3.86	3.61	3.53	3.49	3.46	3.41	3.36
200	3.49	12.01	6.95	5.27	4.43	3.93	3.60	3.36	3.18	3.04	2.93	2.43	2.27	2.18	2.13	2.03	1.93
300	5.24	16.68	8.99	6.47	5.21	4.46	3.96	3.60	3.33	3.12	2.96	2.20	1.95	1.83	1.75	1.60	1.45
345	6.02	18.92	10.00	7.10	5.65	4.78	4.21	3.80	3.49	3.25	3.06	2.19	1.91	1.76	1.68	1.50	1.33
500	8.73	27.06	13.70	9.45	7.34	6.08	5.25	4.65	4.20	3.85	3.57	2.32	1.91	1.70	1.57	1.32	1.07
1000	17.45	62.42	26.75	17.73	13.41	10.85	9.16	7.95	7.05	6.35	5.80	3.29	2.45	2.04	1.79	1.29	0.79

mechanical lateral scanning (as would be the case with spot LMDs) is required. The geometry of such a setup is the same as the one shown for the observer in Fig. 1.

Measurement-field angles of spot LMDs, β, are typically in the range of 1° (and below), while that angle may increase to 40° (with wide-angle lenses; typically 20° and below) in the case of imaging LMDs. When such instruments are applied to the evaluation of lateral variations of luminance and chromaticity, directional effects may become pronounced at the periphery of the field of measurement even in the case of planar DUTs (see Fig. 1). In the case of convex cylindrical samples, the angle θ_i (angle of inclination) varies even more across the field of measurement, as illustrated in Fig. 6. In the case of concave cylindrical DUTs only, this variation is reduced when the LMD is located on the cylinder axis.

When the directional variations of the DUTs are known (see Figs. 2 and 3 and Table 2), we can determine the minimum working distance that corresponds to a maximum permitted angle of inclination and thus to the amount of luminance variation caused by directional variations; but not, however, by lateral variations.

If the percentage of directional effects on the lateral variation of luminance is supposed to stay below 1 percent for the OLED display and 2 percent for the LC display (see Table 1), the distance between LMD and DUT has to be adjusted according to the values obtained from Eq. (1) (cylindrical DUT) and Eq. (2) (planar DUT).

In order to make such measurements reproducible, the parameters according to Table 3 have to be evaluated and specified.

When concave cylindrical DUTs are measured, the variation of the local angle of inclination is generally reduced. With the LMD positioned in the center of the concave cylinder, every location on the DUT within the vertical plane containing the optical axis is measured from the normal direction, which means that for this special geometrical condition, there is no variation of θ_i at all.

Imaging LMDs have been calibrated by the manufacturer of the instrument in such a way that the luminance (radiance) of a uniform planar light source produces a uniform array of output values. During that calibration, the LMD is focused on the plane of the light source. It also must be ascertained during calibration that the aperture of the LMD is overfilled by the light entering from each DUT area element. Deviations from those conditions may result in measurement errors (for example, focusing errors). The effect of defocusing during the measurement of cylindrical samples has been analyzed in detail by Yu *et al.*[4] They concluded that the measurement uncertainty is dominated by the characteristics of the cylindrical DUT, namely the directional characteristic of emission and the cylinder radius. Uncertainties increase with

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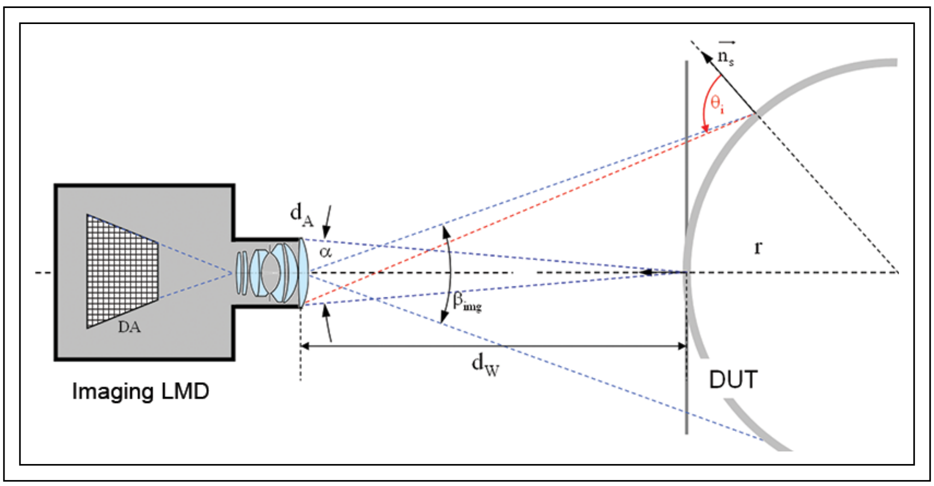

***Fig. 6:** Here, an imaging LMD is applied for the evaluation of,* e.g., *the luminance of a cylindrical DUT. With the measurement field angle, β_{img}, up to 40° (typical 20°), the variation of the angle of inclination across the DUT is more pronounced and thus affects the results. In addition, the area element at the periphery of the measurement field is more distant from the lens than the on-axis area element and thus defocusing takes place.*

Table 2: The decrease of luminance with angle of inclination relative to the normal direction from the results shown in Fig. 2 and Fig. 3.

DUT	Inclination	5°	10°	20°	30°
OLED Display		1%	4%	13%	28%–35%
LC Display		2%	5%	19%–32%	43%–58%

Table 3: The above items and parameters should be specified for DUT, LMD, and setup.

	Specifications	
DUT	**LMT**	**Setup**
Test pattern	Aperture area	MF diameter and location
Temperature	MF angle	Measurement distance
Location of cylinder axis, radius of cylinder	Data acquisition timing	Intersection of optical axis
Software settings, *e.g.*, rendering intent		Measurement direction

continued from page 25

increasing curvature (decreasing radius) and at the edges of the cylinder.[4]

Measurements Under Ambient Illumination

A further complication in measurement of non-planar displays is added when reflective displays are measured or when the performance of emissive displays has to be evaluated under ambient light illumination. In that case it must be ascertained that the illumination conditions (hemispherical diffuse or directional) are uniform over an area that is larger than the measurement field. Several papers concerning measurements of reflective displays under hemispherical diffuse illumination[6,7,8] and the reflective properties of cylindrical emissive displays have been made available through various publications of the SID.[8]

Curved Displays Demand Careful Measurements

Even though non-planar displays do not necessitate the creation of a new chapter of display metrology, they provide strong reasons for a closer look at the components involved in such measurements and the conditions of their application (*i.e.*, measurement setup) in order to specify the relevant parameters completely and in detail, as a basis for reproducible measurement results.

The higher the local curvature of convex cylindrical displays is in the case of spot LMDs, the smaller the field of measurement should be. When directional variations are being evaluated, the increase of the measurement field with angle of inclination has to be considered.

The imaging conditions of imaging LMDs have to be controlled to avoid unintended and uncontrolled mixing of directional and lateral variations of luminance, contrast, and chromaticity, and they have to be specified in detail to make measurements reproducible. The effect of defocus and the related low-pass filtering (blurring) have to be considered when small details (*i.e.*, high-frequency components) have to be identified by imaging LMDs.

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